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Assessment of the Century Scale Sediment Budget of the Brewster Coast

A Report Submitted to the Town of Brewster

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INTRODUCTION

In 2005 the Center for Coastal Studies (CCS) began developing and evaluating a sediment budget-based geomorphic model to determine long-term volumetric coastal change and longshore sediment transport along outer Cape Cod (Giese, et al., 2011). The methodology developed as part of this work was subsequently applied to the Cape Cod Bay coast, and between 2012 and 2014 CCS completed work on assessments of the coastal sediment budget between Provincetown Harbor and Jeremy Point in Wellfleet. These studies demonstrated that comparisons of contemporary bathymetric and terrestrial lidar with high quality 1930s hydrographic and terrestrial data along evenly spaced cross-shore transects provide an effective means of estimating century-scale sediment budgets along Cape Cod Bay shores. The results of these assessments were documented in two technical reports funded by the Island Foundation (IF) (Giese et al., 2012; Giese et al., 2013), and another funded by the Massachusetts Bays Program (MBP) (Giese et al., 2014).

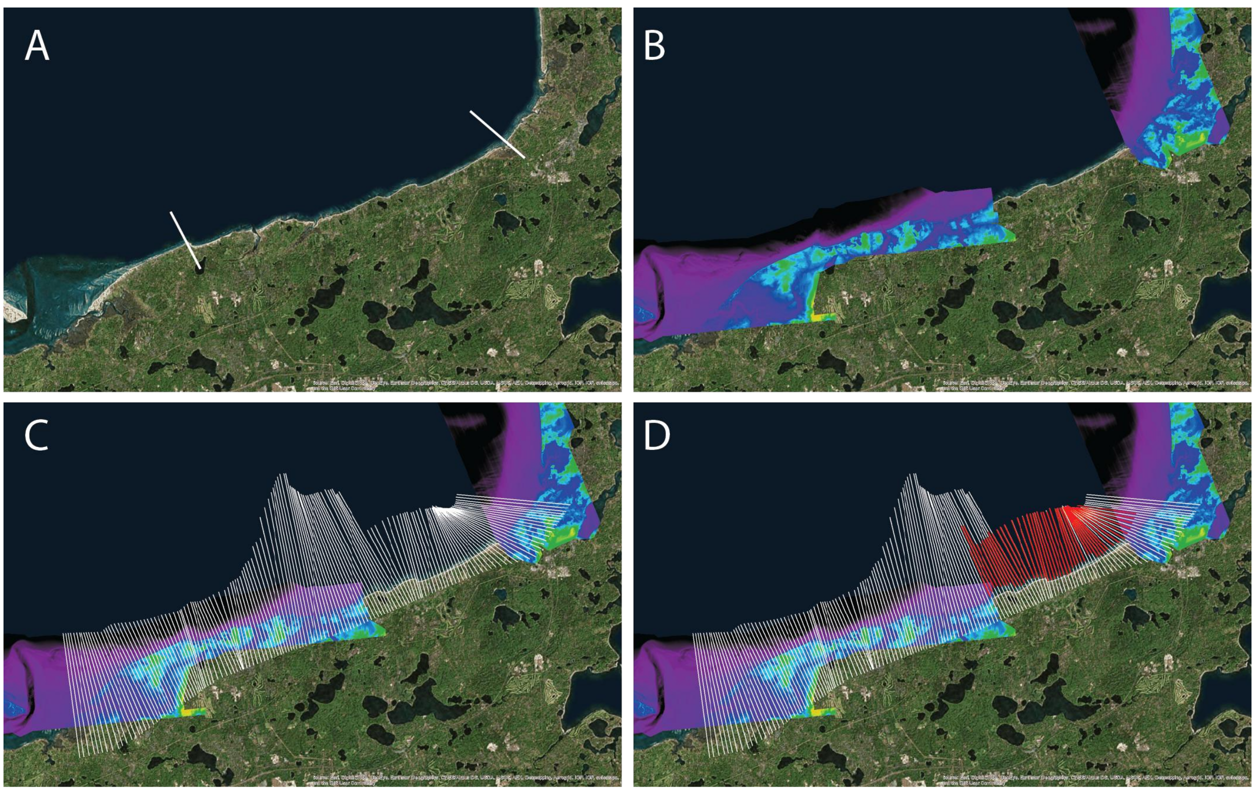


Figure 1: A) Study Area. B) Coverage of 2010 bathymetric lidar within study area. Note area with no bathymetric lidar coverage. C) Study area with transects. D) Red transects in area with no lidar coverage. Bathymetric data was collected via vessel-based acoustic surveys along these transects.

As shown in Figure 1(A), the present study conducted for the Town of Brewster and funded by the Coastal Resiliency Grants Program of the Massachusetts Office of Coastal Zone Management (CZM) extends east from the Nobscusset Point/Chapin Beach area of East Dennis to Rock Harbor in Orleans. While the focus of this work is the Brewster shoreline, it was necessary to extend the analysis slightly to the east and west in order to develop a preliminary sediment budget for the Brewster shoreline. Notwithstanding the need to expand the scope of inquiry, the results of this study provide a quantitative assessment of sediment transport and sediment budget for approximately 15.5 km (9.3 miles) of the southerly Cape Cod Bay coast. This information is vital to an understanding of the historical conditions that contributed to the present position, shape and size of the coastline, and will contribute to estimating future changes. Accordingly, these data can be used to reduce the vulnerability of communities and ecological systems to the impacts of a changing climate and rising sea levels.

METHODOLOGY

As discussed above, the present study represents an extension of work completed previously by CCS for the northerly coast of Cape Cod Bay. Like the earlier work, it is a contribution to the Center's long-term goal to define longshore sediment transport processes and "littoral cells" for the entire shore of Cape Cod Bay that have been discussed and described quantitatively by Berman (2011). The geomorphic model employed has been discussed in previous reports (e.g., Giese et al., 2011) and is introduced here as a framework for presenting the project's historical data compilation and processing.

Theoretical Model Framework

The sediment budget-based geomorphic model applied to the Cape Cod coast in this study is based on the conservation of mass, coastal wave mechanics, and the coastal morphodynamic concept of transport within littoral cells. It can be used to quantify the longshore sediment transport rates, sediment sources and sinks, and the boundaries between littoral cells. The model depends upon two fundamental principles: 1) the smooth, regular form of most exposed sandy coasts is primarily the product of wave action and 2) waves striking the coast at an angle produce a flow of sediment along the shore in the direction of wave travel.

The net flow of sediment along the coast over an extended time period, generally annualized, is termed *littoral drift* or (*net*) *longshore sediment transport*. This transport is quantified in the model as the volume rate (e.g., cubic meters per year) of sediment crossing a shore-perpendicular transect that extends across the active coast from the landward limit of wave-produced sediment transport, and is designated, $\boldsymbol{Q}$.

Coastal erosion and deposition do not depend directly on the magnitude of $\boldsymbol{Q}$, but rather on its rate of change alongshore, $d\boldsymbol{Q}/dy$ (cubic meters per meter per year), that is, the slope of $\boldsymbol{Q}$ when it is plotted against alongshore distance, "y". Erosion results when transport, $\boldsymbol{Q}$, increases alongshore (i.e., $d\boldsymbol{Q}/dy$ is positive); deposition results when $\boldsymbol{Q}$ decreases alongshore (negative $d\boldsymbol{Q}/dy$). This relationship can be expressed explicitly as

$$dA/dt = - d\boldsymbol{Q}/dy$$

where "dA/dt" (square meters per year) is the time ("t") rate of change in cross-sectional area ("A") between two cross-shore transects at a single location.

In addition to the role of sediment transport change along the shore, a shore-perpendicular transect typically gains or loses area due to (*net) cross-shore transport* of sediment such as wind-transported sand exchange between a beach and coastal dunes, tidal inlet losses, or offshore transport of very fine sediment by turbulent seas during storms. These gains or losses are designated by $\boldsymbol{q}$, defined as the net cross-shore transport per unit shoreline distance (square meters per year). The change in cross-sectional area at any point along the shore depends upon the total contributions of longshore and cross-shore sediment transport at that location:

$$dA/dt = - d\boldsymbol{Q}/dy - \boldsymbol{q}.$$

To simplify this relationship, we introduce the symbol, $\boldsymbol{E}$, to represent the negative of "dA/dt", the volume rate of coastal change per unit shoreline distance, i.e., erosion. Substituting, this gives

$$\boldsymbol{E} = d\boldsymbol{Q}/dy + \boldsymbol{q}.$$

Application of this expression along a coastal segment enables a volumetric analysis of shoreline change, a 3-dimensional estimate of change as opposed to the more common 2-dimensional view that results from a linear analysis of shoreline advance or retreat. If the segment is sufficiently large to contain an entire littoral cell including all source regions, transportation paths and sinks, then integration of $d\boldsymbol{Q}/dy$ can yield the total values of $\boldsymbol{Q}$ at each point along the shore. At the updrift and downdrift cell boundaries are points where $\boldsymbol{Q}$ equals zero; these are termed "null points" (Dean and Dalrymple, 2002), and their location is required for a meaningful evaluation of $\boldsymbol{Q}$ at other locations.

Cell boundaries in source regions, or null points in net longshore sediment transport, can be located by considering the implication of our initial assumption that net longshore sediment transport results from waves striking the coast at an angle, thereby producing a flow of sediment along the shore in the direction of wave travel. When referring to the long-term sediment flow at any particular coastal location (as we are in this study), the actual waves concerned are the composite of all waves that acted on that shore over the entire time period of the study. We replace those "actual" waves with a single "model" wave which, acting continually over that time period, would have produced the same net sediment flow. Thus, the littoral cell boundaries (null points) in source regions are located at those locations where the model waves approach onshore in a direction that is at right angles to the shoreline, i.e., the angle, "θ", between wave approach and a line drawn perpendicular to the shore is zero.

This specific relationship between longshore sediment transport, $\boldsymbol{Q}$, and wave angle, “θ”, is consistent with the general expression between the two (e.g., Komar, 1998):

$$\boldsymbol{Q} \sim \sin 2\,\theta.$$

At the null point, “θ = 0”. Since the derivative of “sin 2 θ” is proportional to “cos 2 θ”, it follows that

$$d\boldsymbol{Q}/dy \sim \cos 2\,\theta.$$

Thus $d\boldsymbol{Q}/dy$ is maximum at the null point ($\theta = 0$).

Model Adjustment

Numerical integration of $d\boldsymbol{Q}/dy$ to calculate $\boldsymbol{Q}$ is valid when the transects are approximately perpendicular to the coastline and parallel to each other, conditions not met in the eastern section of the Brewster study area (Figure 1). Therefore for this study, $\boldsymbol{Q}$ was calculated by summing $\Delta\boldsymbol{Q}$ values derived individually for each pair of transects. $\Delta\boldsymbol{Q}$, in turn, is the annualized change in volume between transect pairs - found from (1) the vertical change between profiles along each of the two transects and (2) the horizontal distances separating them - reduced by the volume lost due to cross-shore processes at each transect pair segment of the study area. Details are provided below in “Transect Construction, Volumetric Analysis and Sediment Flow Calculation.”

Historical Data Compilation and Processing

Based on previous work of CCS in Cape Cod Bay, the historical base map for the current study was developed from hydrographic and terrestrial data sets compiled for the period 1933 – 1940. Four hydrographic surveys were conducted in eastern Cape Cod Bay by the USC&GS (predecessor to NOAA’s Coast Survey) during 1933-34 (Figure 2). These surveys were combined with adjacent terrestrial information provided on USC&GS topographic surveys (T-sheets), U.S. Geological Survey (USGS) Quadrangles, and U.S. Department of Agriculture, Natural Resource Conservation Service (USDA-NRCS) 1938 aerial photographs to provide a relatively seamless, synoptic coverage of the entire Cape Cod Bay study area.

Historical hydrographic survey data were downloaded from the NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html), including Descriptive Reports, color image Hydrographic Smooth Sheets (H-Sheets), digital point data in ASCII XYZ format, and metadata. Original survey data were compiled at scales of 1:10,000 (or in some cases 1:5,000) and related horizontally to the North American Datum of 1927 (NAD27) and vertically to local mean low water (MLW) for the geographic area covered by each survey.

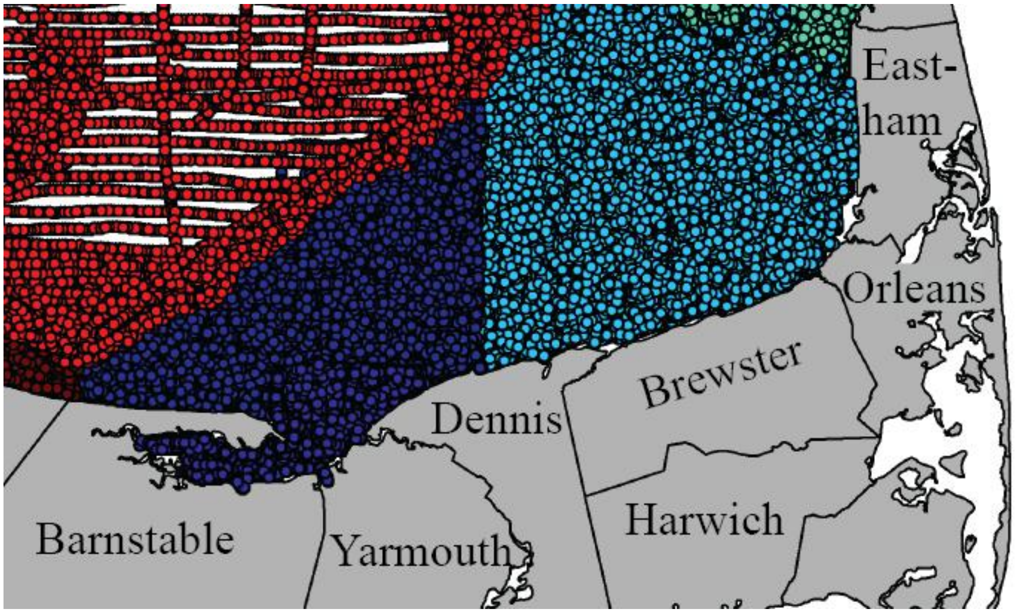


Figure 2: NOAA Hydrographic Survey Point Coverage for Cape Cod Bay, Massachusetts (Red shades denote 1940 surveys. Blue shades denote 1933-34 surveys).

The historical terrestrial data used to characterize the limited area of the land-sea interface (i.e., the area influenced by marine and coastal processes) consisted primarily of USC&GS 1933 and 1938 T-sheets, USGS quadrangles surveyed in 1941, and USDA-NRCS 1938 aerial photographs. These post- "Hurricane of '38" photographs were flown on November 21, 1938, near the time of local high water and were used to help identify landforms such as coastal banks and dunes and to verify changes to the terrestrial environment resulting from the record hurricane.

USC&GS T-sheets for the study area (and accompanying Descriptive Reports) were downloaded as non-georeferenced survey scans from the NOAA NOS Special Project web site at http://nosimagery.noaa.gov/images/shoreline_surveys/survey_scans/NOAA_Shoreline_Survey_Scans.html. Similarly, non-georeferenced scans of USGS historical quadrangles were downloaded from the University of New Hampshire at http://docs.unh.edu/nhtopos/nhtopos.htm.

The extent of landside topography incorporated into the historical data sets was limited to the relatively small area of land influenced by marine and coastal processes (the land-sea interface) necessary for the volumetric analysis. While the USGS topographic work provides broad, synoptic coverage of topographic conditions existing at the time of the survey, there are inherent data limitations associated with this mapping effort related generally to the relatively coarse mapping scale and less dense elevation data for early mapping efforts. To minimize these limitations, topographic data obtained from each Quadrangle was supplemented with additional elevation data derived from:

1) USC&GS T- and H-Sheet Descriptive Reports.
2) The elevations of the mean low water (MLW) and mean high water (MHW) lines as obtained from the 1930s Coast Survey T- and H-sheets.

3) Profiles obtained from contemporary survey work to characterize representative beach and bluff profiles.
4) The location of natural features shown on historical T-Sheets and aerial photographs such as the toe of coastal banks and salt marshes, the elevations of which relative to MHW and MLW can be estimated.
5) The elevations of physical features such as road intersections, railroad centerlines, building corners, etc., common to both historical and contemporary data sets and not likely to have changed over time.

Elevation data from these supplemental sources were added to the historical data set and blended with USGS topographic information to increase the reliability and density of the limited landside topography used in the analysis.

As discussed above, comparisons of historical and contemporary hydrographic and terrestrial datasets can be important sources of information for quantifying changes in landform volume and net sediment movement. Where the land and sea interact along the shores of Cape Cod, such volumetric comparisons can be used to estimate long-term, regional scale sediment flux and sediment budgets. To effectively use historical geospatial data, such as those central to the methodology discussed above, however, potential sources of uncertainty inherent in data collection methods must be minimized to ensure that quantitative estimates provide reliable information at the scale of the analysis (Byrnes et al., 2002). In addition to limitations in technology and equipment that could affect data quality, a potential source of significant uncertainty for historical datasets lies with the ability to accurately translate horizontal and vertical reference systems to contemporary datums (Jakobsson, *et al.,*2005).

For this study, all contemporary data is referenced horizontally to the Massachusetts State Plane Coordinate System (North American Datum of 1983 (NAD83)) and vertically to the North American Vertical Datum of 1988 (NAVD88)). Historical data were referenced horizontally to the North American Datum of 1927 (NAD27) and vertically to a local tidal datum (either mean low water (MLW) for the hydrographic survey or mean sea level (MSL) for terrestrial data), requiring translation to the project datums (NAD83/NAVD88).

While the mathematical process for translating horizontally from NAD27 to NAD83 is well established (Giese and Adams, 2007), the process for developing an accurate vertical translation from a local tidal datum to a geodetic datum requires retracing previous survey work. The ability to reproduce elevation data referenced to local tidal datums accurately, whether historical or contemporary, depends on an ability to find and reoccupy reference stations established for the tidal readings. Lacking recoverable reference points (benchmarks), the short term nature of the tidal observations, inter-annual variations in tidal cycles, rising sea levels, and changing environmental conditions make development of reliable translations of local, historical vertical reference systems to contemporary systems problematic and greatly increase the uncertainty associated with quantitative comparisons (Jakobsson et al., 2005; Van der Wal and Pye, 2003). This can be particularly true for volumetric change analyses where rising sea levels can introduce a significant bias towards erosion in the absence of an accurate translation.

To minimize this potential source of uncertainty, all historical data points were translated vertically based on research, recovery, and reoccupation of historical tidal benchmarks identified in the 1930's USC&GS Hydrographic Descriptive Reports. Where benchmarks could be recovered, they were occupied with high accuracy GPS survey equipment to provide a direct translation to NAVD88. When USC&GS tidal benchmarks were found to have been destroyed, the historical record was further investigated to establish relationships to other extant benchmarks that could be occupied. These relationships were used to relate the tidal benchmark to NAVD88 (Mague, 2012).

Benchmarks for historical hydrographic data sets have been recovered and occupied as part of our previous work and the resulting translations to NAVD88 described in Giese et al, 2014(b), Giese at al 2013, Giese et al 2012, and Mague, 2012. The present study required additional field work to recover and occupy a historical benchmark located on Sandy Neck in Barnstable to translate the hydrographic survey covering the westerly edge of the study area from local MLW to NAVD88. Based on research of available technical documents, field work was conducted in May of 2014 and using previous methods (Mague, 2012), Tidal Benchmark 1 set by the USC&GS in 1934 (TBM 1 of 1934) was recovered and occupied (Figure 3).

Figure 3: TIDAL BENCH MARK 1 (1934) is a standard disk, stamped "Barnstable – BM 1/1934", set in the top of a 12"x12"x 3 ½" ft. concrete post, 8" x 8" at top and extending about 4 inches above surface of ground, located on Sandy Neck, Barnstable Harbor (left). GPS reoccupation of TBM 1 by CCS to establish hydrographic survey relationship to NAVD88 (right).

As in previous work, the referenced benchmark was occupied with CCS's Trimble® R8 GNSS Receiver and Trimble® TSC2™ utilizing Real-Time-Kinematic (RTK) GPS techniques and the Keystone Virtual Reference Station Network (VRS) for data collection. Based on the results of an on-going CCS accuracy assessment program, horizontal and vertical root mean square errors (RMSE) values of this system have been determined to be within 2.0-2.6 centimeters.

Based on the fieldwork, a reference to NAVD88 was obtained for the local mean low water value used for the 1930s surveys covering the study area. The translation of hydrographical and terrestrial data for the study area, referenced to a local 1933/34 MLW or MSL datums, to the contemporary geodetic datum, NAVD88, is represented by the relationships in Figure 4:

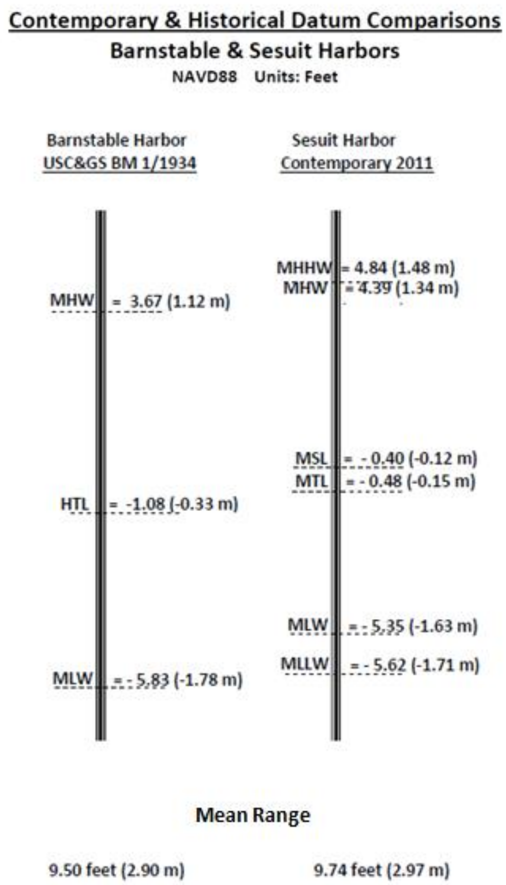


Figure 4. Contemporary and Historical Datum Comparisons for Study Area Units: Feet (meters)

After historical terrestrial data points were digitized, all data points were translated horizontally and vertically and the contributing data sets were combined into one comprehensive file (NAD83/NAVD88) for use in creating a 1930s three-dimensional surface, or surface model. This surface model formed the basis for quantitative comparisons with a similar surface derived from

U.S. Army Corps of Engineers 2010 bathymetric lidar data, 2011 USDA-NRCS Terrestrial lidar data and CCS's 2014 vessel-based acoustic surveys.

Historical 1930s/40s Surface Model

A 3-dimensional model of the historical surface was created using the digital database to create a point shapefile within the ARCGIS v10.0 software suite. These points were then converted into a Triangulated Irregular Network (TIN) using the 3-D analyst extension with ARCGIS. These triangles are formed using 3D data from three points to create a plane that represents a real-world surface. The TIN was then converted into a terrestrial or bathymetric raster with latitude (y), longitude(x), and elevation (z) attributes. Since there is rarely 100% coverage of a mapped area, a krigging method was chosen as the best interpolation method for this study and utilized to represent changes in natural topography and/or bathymetry. Before finalizing the surface model, CCS coastal geologists reviewed the surface to identify potential data issues as well as to remove outliers from the final surface. This was found to be a critical step in previous studies to ensure that a processes-based assessment is conducted prior to accepting or rejecting points within the surface and proceeding with the analysis.

Contemporary Data and Surface Models

Contemporary surface models for the study area were compiled from two lidar data sets, one containing the terrestrial data, and the other bathymetric data. The terrestrial lidar was flown in the spring of 2011 by the U.S. Department of Agriculture's Natural Resources Conservation Services. The bathymetric survey was flown in May of 2010 by the U.S. Army Corps of Engineers. As part of its QA/QC program, representative areas of terrestrial lidar data were tested using data collected with the Center's GPS equipment.

Acoustic data were acquired by CCS in areas without bathymetric lidar coverage (figure 1, B and D) using a Tritech PA500/6-S altimeter side-mounted to the R/V Marindin in June and July 2014. The data were processed using Hypack 2014 software and appended to the transect data set using Microsoft Excel 2010. The acoustic data were also collected in areas that overlapped the bathymetric lidar. QA/QC included the comparison of the overlapping 2014 acoustic data with the 2010 lidar data in order to test for offsets.

Transect Construction, Volumetric Analysis and Sediment Flow Calculation

While the historical and contemporary surface models were being developed, a shore-parallel baseline and shore-perpendicular transects were constructed along the 18 km shoreline of the study area and combined with transects of previous studies, as shown in Figure 1. Transects were spaced at 150-meter intervals (approx. 120 transects) and extended out to a depth of 10 meters.

Using the historical surface model and the contemporary lidar data sets, elevations were extracted at 2 meter intervals along each transect. Using MATLAB software, elevations and cross-shore and longshore distances derived from the historical and contemporary data sets were plotted together to determine the local change in sediment volume, ΔV, between adjacent pairs of transects over the intervening time period (77 years). These, annualized, provided ΔV/Δt rates for each segment. Subsequent analysis based on profile comparisons of 1933-1934 and 2010-2011 data, documented changes in sediment volume and form thus permitting estimates of cross-shore gain and loss rates, ***q***, for each segment. The differences between ΔV/Δt and ***q*** at each transect-pair segment yielded estimates of the local rate of change in net longshore transport, i.e.,

$$\Delta \boldsymbol{Q} = \Delta V/\Delta t - \boldsymbol{q} \, .$$

Finally, estimates of the volume, rate and direction of sediment movement along each segment of the shoreline, ***Q***, were determined by summing Δ***Q***, both north and south of the central "null point." Methodology for determination of the "null point" location - delineation of the littoral cell boundaries - is described in "Theoretical Model Framework" above.

RESULTS

Comparisons of two profiles, one historical and the other contemporary, at single transects are provided in Figure 5 and 6. Figure 5 illustrates the extreme erosion occurring in the west of the study area, while Figure 6 shows the reverse, rapid deposition in the east. The reader should recall that "***E*** " (volumetric erosion rate) is defined as the *negative* of area change between profiles, hence a positive value for transect 2418 and a negative value for transect 2178.

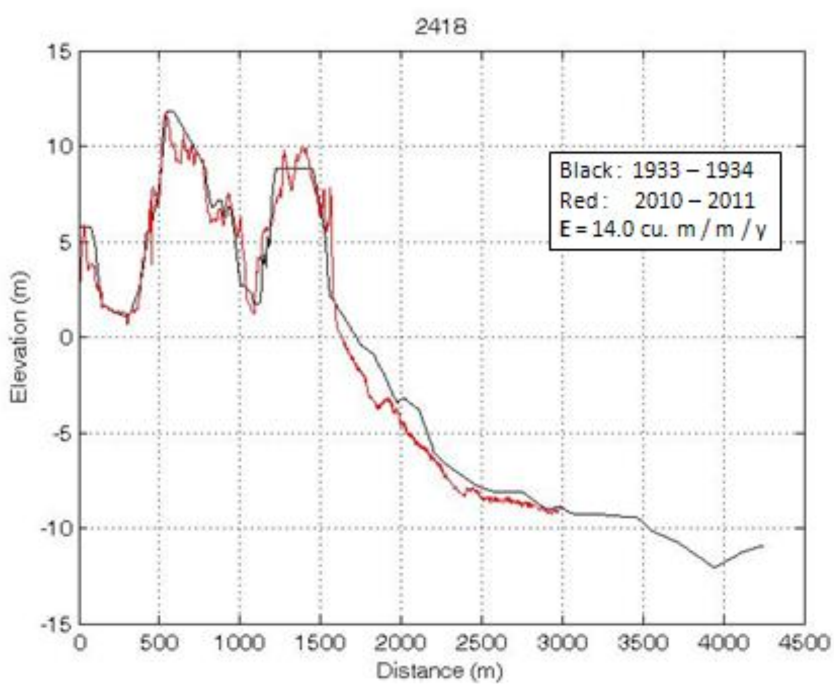


Figure 5: Comparison of historical and contemporary profiles of transect number 2418. Arrows indicate limits of cross-sectional area considered for calculation of *E* value of this transect.

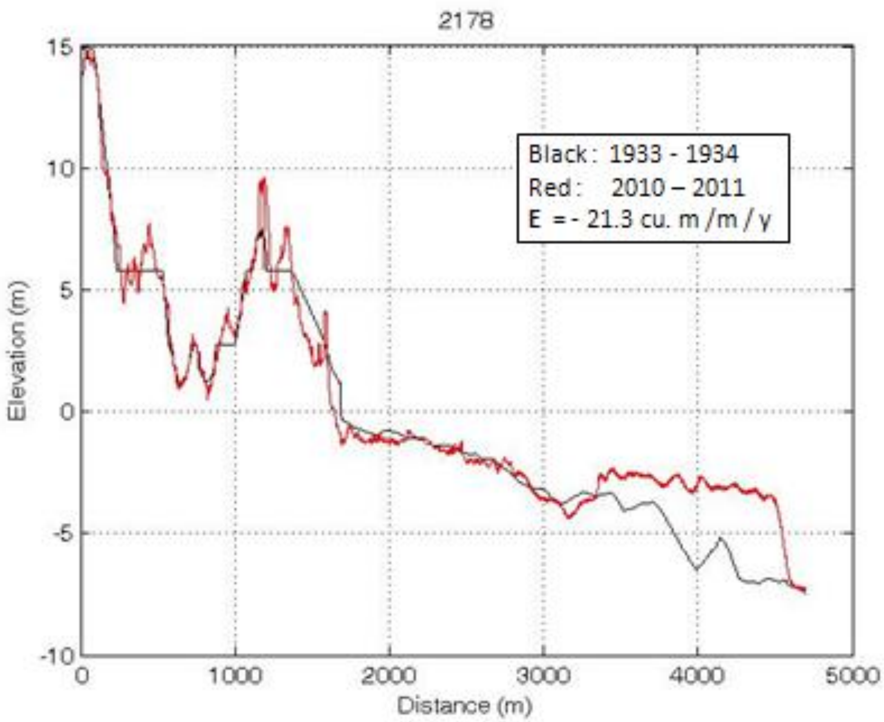


Figure 6: Comparison of historical and contemporary profiles of transect number 2178. Arrows indicate limits of cross-sectional area considered for calculation of *E* value of this transect. The contemporary "2010-2011" profile includes the 2014 bathymetric data described above.

The distribution of volumetric erosion and accretion for the entire study area - beginning at Skaket Beach in Orleans and ending in East Dennis – is presented in Figure 7. The graph shows the results for all transects; the significance of the individual green, blue and red lines is discussed below in "Discussion."

Finally, in Figure 8, we present the results of our calculation of "***Q***", the rate of net alongshore sediment transport throughout the study area. Geographic points-of-interest are superimposed to assist interpretation and application to management issues. Negative "***Q***" values indicate eastward transport; positive values, westward transport. Sections in red are primarily characterized by increasing "***Q***" values. These are areas of erosion – source areas for the littoral drift in the region. Similarly, the green sections (decreasing "***Q***") are primarily areas of accretion, while black denotes fairly constant net transport with little total erosion or accretion. Red dots designate the "null points" determined as explained in "Methodology"; net transport rates vary from zero at those locations to a maximum of almost 30,000 cubic meters per year near Brewster's western boundary at Quivett Creek.

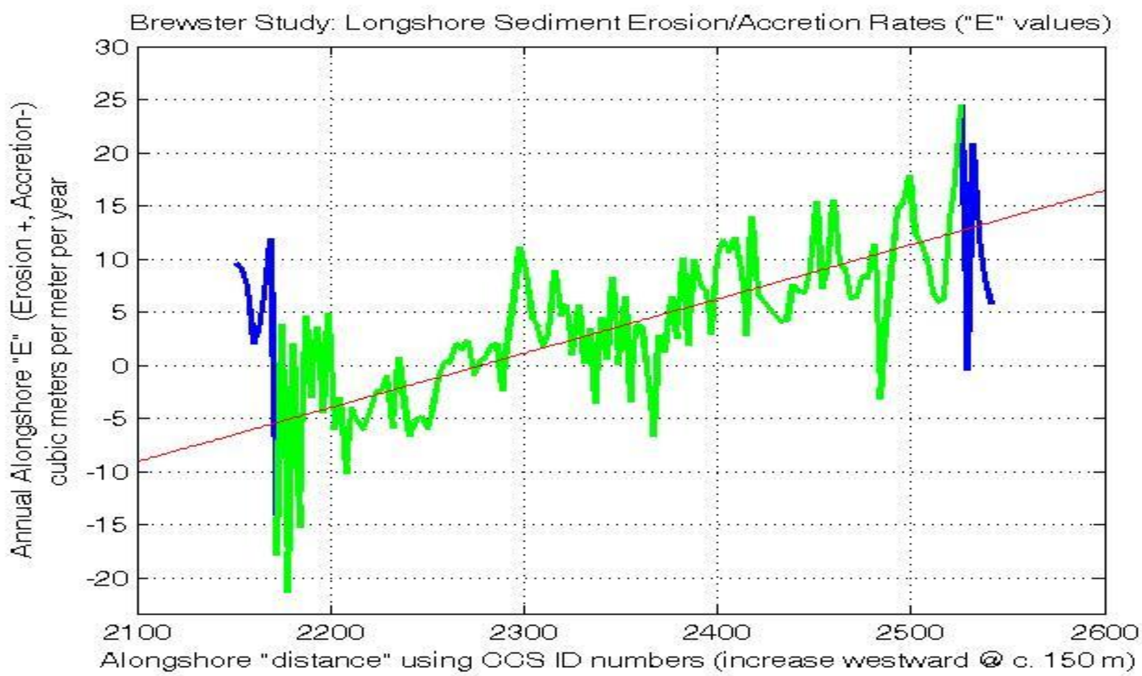


Figure 7: Distribution of *E* for all transects.

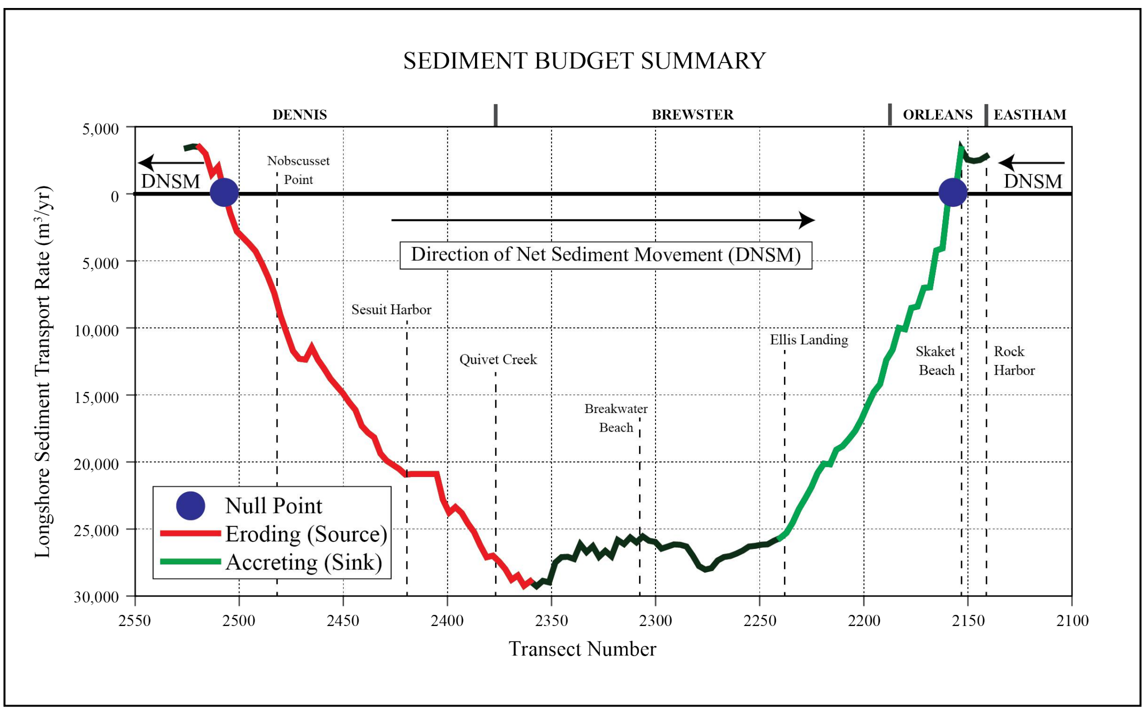


Figure 8: Distribution of *Q* for all transects.

DISCUSSION

The results of this study provide insight into the sedimentary conditions and processes associated with the Brewster coast of Cape Cod Bay. As shown in Figure 8, they indicate that this coast occupies more than half of a littoral cell, the “Brewster Cell”, in which sediment flows eastward from a source null point lying between Nobscusset Point and Chapin Beach in Dennis, and a sink null point near Rock Harbor in Orleans. Since the prevailing winter wind direction in Cape Cod Bay is northwesterly, very likely this eastward flow of sediment is primarily driven by northwesterly wind waves.

Figure 7, presenting volumetric erosion and accretion rates for the entire study area, shows those rates for the Brewster Cell in green. The red line, a linear best-fit to the Brewster data, reveals a strikingly regular trend of erosion decrease and accretion increase from source to sink throughout the cell. Also apparent from the figure is the dominance of erosion over accretion. This sediment imbalance within the cell is primarily the result of cross-shore sediment transport, ***q***. Some of the “missing” sediment is carried onshore by wind to dune fields and by tides into estuaries (Figure 9); while other sediment, primarily the finer constituents, is transported to offshore deposits by turbulent winter seas.

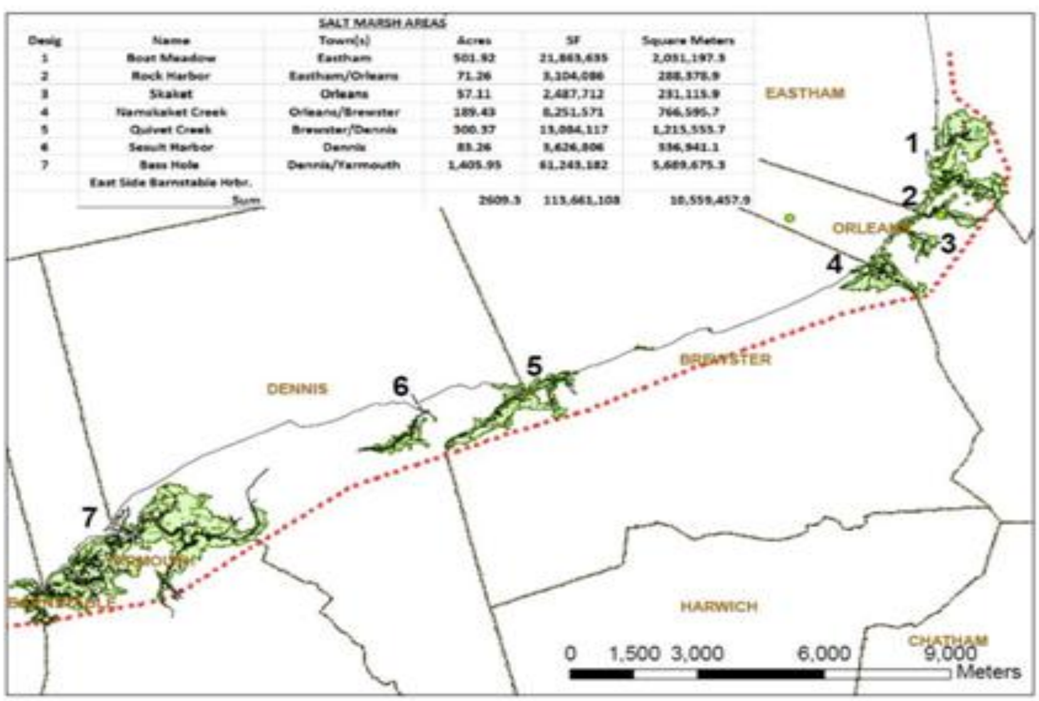


Figure 9: Marsh deposits within the study store sediment transported landward from the active coast into the regional estuaries.

The model employed in this study (a "1-D model") averages long term net transport across the entire width of the active coast. It indicates that the Town of Brewster, at its westerly boundary, receives sediment eroded from the coast of the adjoining Town of Dennis. Eastward sediment transport maintains a fairly constant rate of between 25,000 and 30,000 cubic meters per year throughout the western half of the Town's coastline, and then decreases to some 10,000 cubic meters per year at the Town's eastern boundary. This reduction in transport rate indicates that some 15,000 to 20,000 cubic meters of sediment per year are added to eastern section of the active Brewster coast. However, all available data indicate that the deposition occurs offshore of the Brewster shoreline.

Figure 10, based on a section of NOAA chart 13250, shows several major areas of deposition offshore along the front, and most significantly along the outer edge, of the large, easterly trending, tongue-shaped shoal (Area #1) associated with the Brewster intertidal flats. Onshore, the chart indicates exposed boulders in the nearshore zone (Area #2), suggesting erosion rather than deposition there. Shoreline and nearshore erosion along the eastern section of the Brewster coast is confirmed by our comparison of historical and contemporary profiles along transects in that section (e.g., Figure 6).

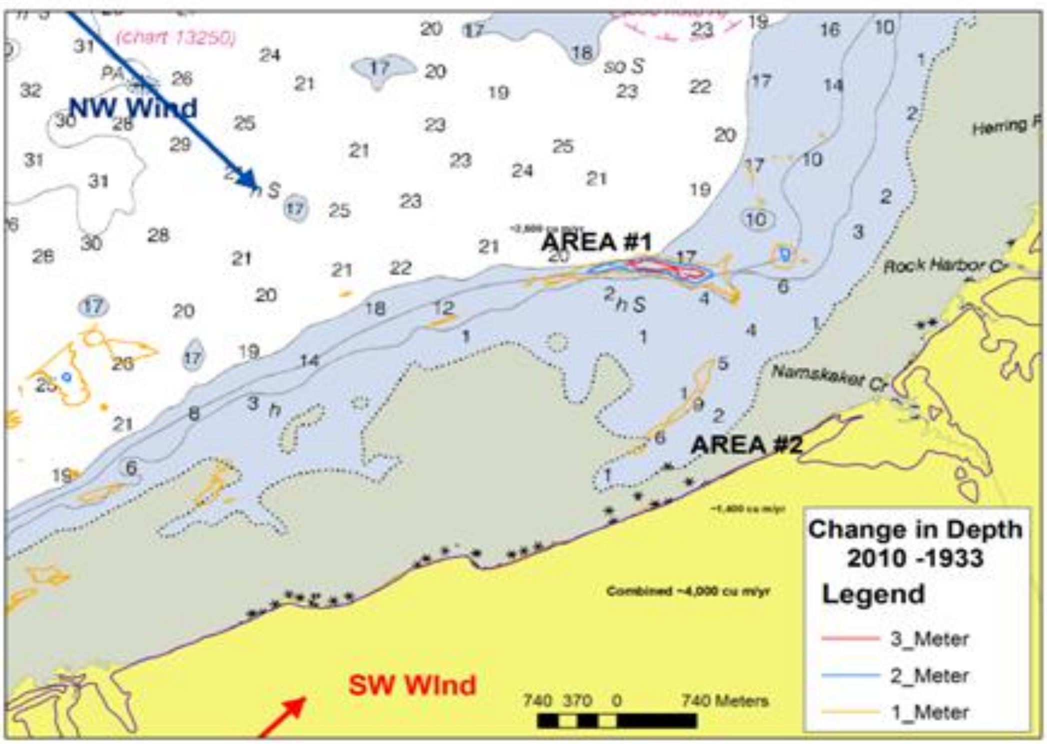


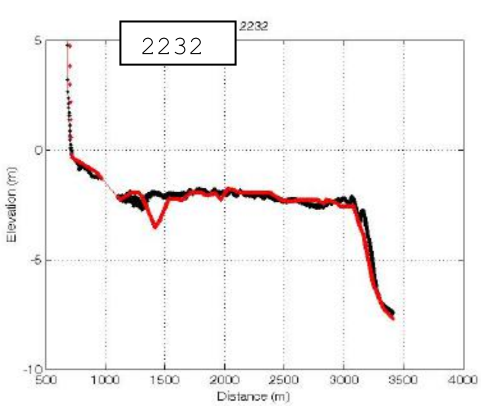
Figure 10: Portion of NOAA chart 13250 showing offshore areas of deposition identified in this study, and exposed boulders (indicating coastal erosion) in the nearshore.

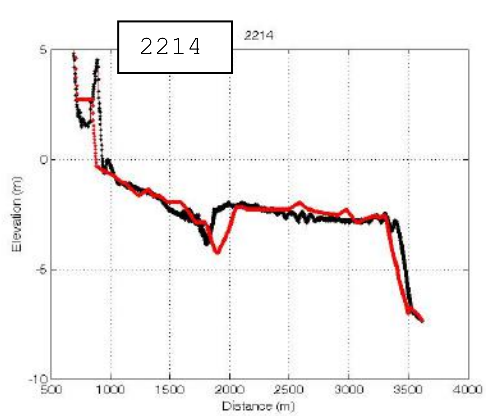
Namskaket Shoal

The tongue-shaped shoal is shown in cross-section in Figure 6. To better define this feature, which we tentatively refer to as Namskaket Shoal, Figure 11 provides a series of cross-sectional plots of the sea floor covering the area of converging transects lying in the vicinity of Namskaket Creek (Figure 1). This shoal has the basic characteristics of fluvial bed forms known as *linguoid bars*, found in rivers transporting large volumes of sediment at locations of increasing river width. In Figure 11, color codes for the profile dates are reversed from those used earlier (e.g., Figure 6); the 2010-2011 profile is shown in black; the 1933-1934 profile in red.

The eight plots in Figure 11 cover the area extending eastward from transect 2232 to transect 2166, located geographically in Figure 8. The contemporary (black) profiles indicate that at the present time the distinct tongue-shaped deposit first appears after - east of - transect 2232 and ends west of transect 2166, i.e., between transects 2214 and transect 2172. Within that region the shoal is clearly bounded offshore by a steep slope extending to depths greater than 7 m., and inshore by a shallow declivity separating it from the landward inter-tidal flats.

In contrast, the red profiles indicate that at 1933-1934 distinctive tongue-shaped form was present farther eastward, at transect 2232, than at present; also that it terminated farther eastward than a present - after transects 2190. Summarizing, we find that in 1933-1934 the shoal's form was well defined between transects 2232 and 2190, while at present it is well defined between transects 2214 and 2172. In addition to this longitudinal, alongshore extension of the shoal, a comparison of the profiles reveals a lateral, primarily offshore, extension that increases eastward. Taken together, these observations suggest that Namskaket Shoal is a growing and eastward migrating depositional feature. Since it lies southeastward of the gradually submerging Billingsgate Shoal (Uchupi, et al., 1996), it seems likely that the development of Namskaket Shoal is closely tied to an increase in energy of wind waves produced by the prevailing winter northwesterlies.





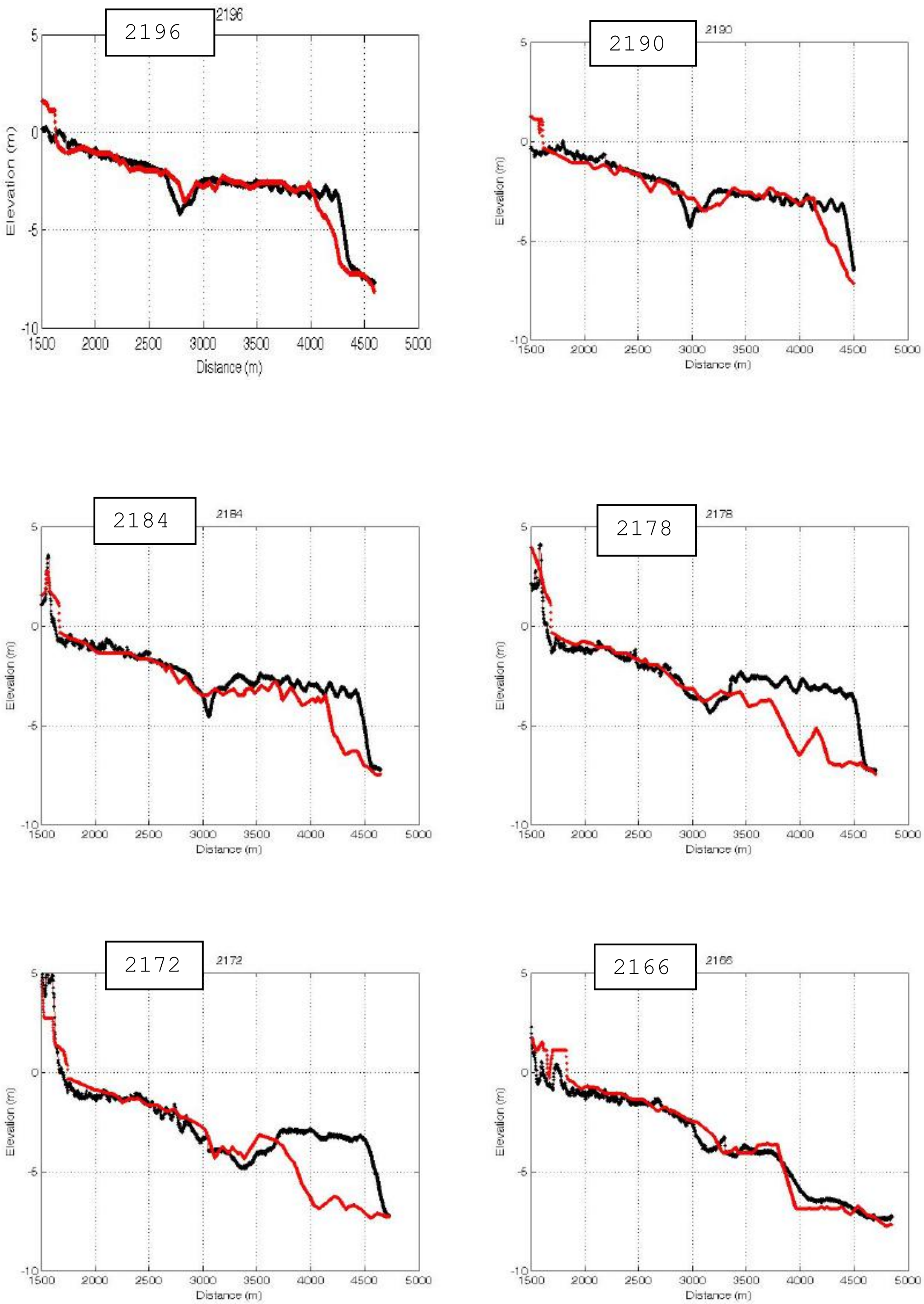


Figure 11: Eight cross-shore transects lying in the vicinity of Namskaket Creek beginning, in the east, with transect 2232 and ending in the west with transect 2166. Transect profiles representing 1933-1934 conditions are shown in red; contemporary (2010-2011) profiles are shown in black. The significance of these profiles are discussed in the text.

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GLOSSARY OF TERMS

Term	Symbol	Units	Description
Alongshore gradient of annual net longshore transport	d***Q***/dy	meters^2/year or meters^3/meter/year	The slope of ***Q*** when it is plotted against alongshore distance "y". It describes the gains or losses in area at a shore-perpendicular transect due to longshore sediment transport. If **q** = 0, erosion results when d***Q***/dy increases alongshore (i.e., positive d***Q***/dy); deposition results when d***Q***/dy decreases alongshore (i.e., negative d***Q***/dy).
Negative of annual rate of change in cross-shore area	***E***	meters^2/year, or meters^3/meter/year	Total loss (+) or gain (-) per year in cross-sectional area of the "active" zone (wave transport zone) of beach at any specific location along the shore. Equals d***Q***/dy + ***q.*** (+) E = erosion; (-) E = deposition or accretion.
Annual rate of change in cross-shore area along a transect	dA/dt	meters^2/year or meter^3/meter/year	Time ("t") rate of change in cross-sectional area ("A") between two cross-shore transects at a single location or the volume rate of coastal change *per unit* shoreline distance. (Note: dA/dt = - d***Q***/dy – ***q***).
Littoral cell			A coastal compartment that contains a complete cycle of sedimentation including sources, transport paths, and sinks. Cell boundaries delineate the geographical area within which the sediment budget is balanced, providing the framework for the quantitative analysis of coastal erosion and accretion. (See Berman, 2011, for full discussion)
Littoral drift or (net) longshore sediment transport	***Q***	meters^3/year	The annual net flow of sediment along the coast expressed as the volume rate of sediment crossing a shore-perpendicular transect that extends across the active coast from the landward limit of wave-produced sediment transport seaward to the approximate limit of sediment movement. (The result of the integration of d***Q***/dy along the shore). The model assumes that net longshore sediment transport results from waves striking the coast at an angle, thereby producing a flow of sediment along the shore in the direction of wave travel.

Local rate of rhange in net longshore transport - estimate	$\Delta \boldsymbol{Q} = \Delta V/\Delta t - \boldsymbol{q}$	meters^3/year	Where $\Delta V/\Delta t$ represents the local change in sediment volume, ΔV, between adjacent pairs of transects over the intervening time period, Δt (77 years).
Long-term sediment flow			At any particular location along the shore, the result of the composite of all waves (i.e., the actual waves) that acted on the shore over the time period of the study
Model wave			A theoretical single wave representing the composite of all "actual" waves which, acting continually on the shore over the time period of the study, would have produced the same net sediment flow as the actual waves.
Net *cross-shore* transport per unit shoreline distance	$\boldsymbol{q}$	meters^2/year or meters^3/meter/year	Gain or losses in area at a shore-perpendicular transect due to cross-shore sediment transport , *e.g.*, wind-transported sand exchange between a beach and coastal dunes, tidal inlet losses, or offshore transport of very fine sediment by storm seas.
Null point			A point along the shore that defines the updrift or downdrift boundary of a littoral cell. Where $\boldsymbol{Q} = 0$, or $d\boldsymbol{Q}/dy$ is a maximum (in the case of a source). Located where model waves approach shoreline at right angles, i.e., the angle, "θ", between wave approach and a line drawn perpendicular to the shore is zero. This point is sometimes referred to as a nodal point.
Wave angle	θ		The angle between wave approach and a line drawn perpendicular to the shore

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